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Finite element modeling of the human cervical spinal column: Role of the uncovertebral joint †

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Abstract

The cervical intervertebral disc has a unique feature in that a fissure or cleft runs along the uncinate process toward the nucleus pulposus called the uncovertebral joint. A three-dimensional finite element model for the multi-level cervical spine is developed for the purpose of investigating the biomechanical significance of the uncovertebral joints. The original disc model is modified to simulate the absence of the uncovertebral joints (UJRM) by replacing the fissures with continuous annulus fibrosus. The absence of the uncovertebral joints results in decreased motion in all loading modes and C3/C5 segment is most affected. The differences (normalized by the results from the original disc model) between the original disc model and UJRM in rotation are -3.9, -6.1, -14.0 and -24.4% for 1Nm of flexion, extension, axial rotation and lateral bending moment, respectively. The uncovertebral joint tends to increase the coupled motion in lateral bending motion, but the coupled motion difference varies depending on the level of motion segment in axial rotational motion. Data derived in this analysis can help promote improvement of designing total disc replacement devices.

Keywords: Uncovertebral joints; Cervical spine; Finite element model; Range of motion

1. Introduction

The human vertebral disc is a unique structure in the spine that bears weight and allows motion. It is made of a central portion (the nucleus pulposus) which is surrounded by layers of tissue (the annulus fibrosis). The disc serves to help the spine support the body and allows relative movement between vertebrae.

The nucleus pulposus contains a hydrated gel–like material which allows it to bear weight and transfer load which is similar to pressing on a water balloon. The annulus fibrosus is a strong radial tire–like structure made up of lamellae; concentric sheets of collagen fibers connected to the vertebral end plates. The sheets are orientated at various angles. In the thoracic and lumbar regions, the intervertebral discs have the same structure, although they vary in size.

The cervical discs (from C2/3 to C6/7) do not extend to the lateral margins of the vertebral bodies where they are interconnected. In this lateral area, during childhood, uncinate processes grow from the vertebral body below each disc to make contact with the lower lateral margins of the vertebral body above each disc. These processes form adventitious joints with bursa-like synovial cavities (termed uncovertebral joints) at the lateral margins of typical cervical intervertebral discs [1].

The cervical spine is distinct from the thoracic and lumbar spines involve uncinate process and angle of facet joint as well as the uncovertebral joint. These unique structural features allow a large degree of relative movement between the vertebral bodies.

The uncovertebral joints are placed in both of lateral sections and engaged with the uncinate process of the vertebral body. In the internal structure of the joint a fissure extends across lateral sections. The fissure is filled with synovial fluid and enclosed by a membrane. In the recent histological study on the uncovertebral joint, the presence of both synoviocytes and chondrocytes in the tissue associated with the uncovertebral complex suggests that the joint may be synovial in nature [2], even though further histological evaluation remains yet to be done to definitively classify the articulation as a synovial joint.

Kumaresan et al. [3] reported that the volume of the uncovertebral joint ranges between 50~100mm^3, which is considerably small compared to the volume of the disc. However, their study was limitedly conducted in understanding the role of the uncovertebral joint in spine biomechanics. The joint has not been addressed in a majority of previous experimental and analytical studies, and the origination and functionality of the

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joint still remains yet to be proved. To the best knowledge of the present authors, the first systematic study on the joint was conducted by Clausen et al. [4]. In their study, one motion segment (C5/C6) based FE model of the lower cervical spine was designed to enable biomechanical analysis including uncovertebral joints and uncinate processes. In the model the uncovertebral joint is realized by gap elements. However, the gap element is not fully adequate for the uncovertebral joint, which is synovial joint.

Since the size of the uncinate processes varies with the corresponding segmental level, a full cervical vertebrae model is required to properly understand the role of uncovertebral joints in the whole cervical spine kinetics. The aim of the present study is to develop a whole cervical spine FE model for biomechanical analysis and subsequently explore the role of the uncovertebral joint.

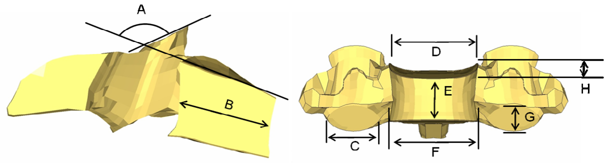
2. Method

The whole cervical spine was meshed using HyperWorks (Ver. 10.0 Altair engineering Inc., Troy, U.S.A.), and the simulation was carried with ABAQUS 6.9 (Dassault Inc., France). The configuration of vertebrae of the cervical spine adopts Non-uniform rational B-Spline (NURBS) human anatomy model (Digimation co., FL, U.S.A.) [5], which is based on average-sized western adult male. C0-C2 controls 50% of motion of cervical column and they are distinct from the other cervical spine (C3~C7) in shape. 4 node solid element (C3D4) is used for C1 and C2 vertebrae to realize its geometrical complexity. Cortical bone and cancellous bone are, respectively, modeled and set to the corresponding material properties. Since facet joint orientation, intervertebral disc height variation and three-dimensional morphology of the vertebra largely contribute to biomechanical behavior of the cervical spine, their quantitative anatomy is critical to the present study. From the experimental studies by Milne [6], Gilad and Nissan [7] the morphological features of the cervical vertebrae including the facet angle, uncinate process height, and vertebrae body size are adopted. Each respective cervical vertebra is meshed with 8 node solid element (C3D8), and the cortical bone of the vertebrae body is meshed with 4 node shell elements (S4) with 1 mm of thickness. The sizes of the present vertebrae model are listed in Table 1.

Annulus fibrosus is a fiber-imbedded annulus ground matrix, and it tends to bulge in response to the pressure from nucleus. To realize the bulging behavior, nucleus is modeled with 8 node solid element (C3D8H). Four stacked layers of the annulus ground matrix are meshed with 8 node solid element (C3D8), and the fibers imbedded in the layers are meshed with 2 node truss element (T3D2) laid on the horizontal plane and configured to cross at 30^{o} and 150^{o}. The volume ratio of the fiber of each respective segment to annulus fibrosus is set to 20%.

Based on Kumaresan et al.'s work [3], the uncovertebral joint of the present model is placed in lateral sections of both

Table 1. Sizes of the vertebrae models.



	C3	C4	C5	C6	C7
Disc-Facet angle (A)	130.2	140.0	129.9	126.1	116.4
Vertebral body depth (B)	18.1	18.5	20.6	21.6	22.2
Facet width (C)	14.8	13.3	15.2	14.5	15.1
Bi-uncinate diameter (D)	23.6	23.9	25.7	26.8	29.1
Vertebral body height (E)	13.8	12.3	13.6	13.2	13.7
Vertebral body width (F)	22.8	24.2	25.4	28.5	27.7
Facet depth (G)	11.4	12.6	10.3	10.3	11.0
Uncinate process height (H)	4.9	4.8	2.5	3.9	3.6

*Sizes are in mm

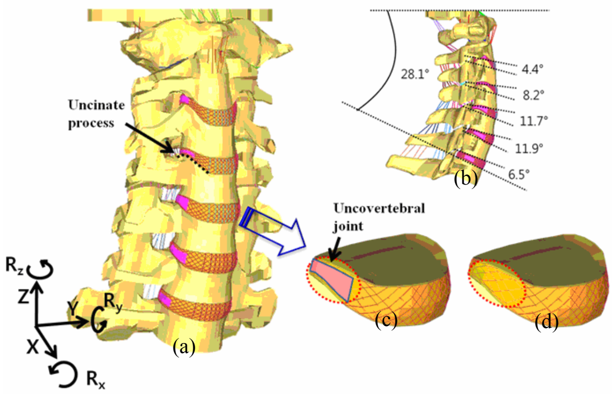


Fig. 1. Developed (A), (B) whole cervical spine FE model including (C) disc model consisted of uncovertebral joints and (D) disc model consisted of annulus fibrosus (UJRM).

sides of each disc and meshed with 4 node fluid element (F3D4) and 4 node membrane element (M3D4). These modeling techniques provide more realistic response characteristics than gap elements [8]. The size of the uncovertebral joint is set based on their report. Each disc height is determined using the data from the work by Pooni et al. [9]. The configuration of the cervical spine and the disc is shown in Fig. 1.

Twelve types of ligaments (between C0 (occipital bone) and C1 (atlas)) including anterior atlanto-occipital membrane and posterior atlanto-occipital membrane are modeled with tension-only truss (T3D2) and placed at each corresponding position. The transverse ligament is connected with the anterior part of odontoid process. Laterally, it is bounded to the lateral mass of C1, and at the top, it is bounded to C0, and at the bottom it is bounded to the backside of C2 vertebral body. The ligament forms in a cross shape, allowing C1 to rotate with respect to the axis of the odontoid process. To achieve the specific function and shape of the transverse ligament in the

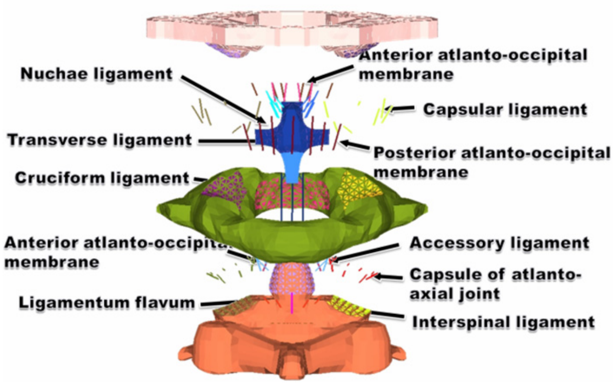


Fig. 2. The locations of the ligaments of the upper cervical spine.

simulation, 3 node shell element (S3) is used to model the ligament. Contact condition is imposed on the odontoid process. The locations of the ligaments of the upper cervical spine are shown in Fig. 2.

Anatomically, the facet joint and the superior articular facet of atlas are placed between C1 and C2 from articulation joint. To simulate this feature, surface-to-surface contact condition is arranged between the articulating surfaces. Nonlinear tension-only truss element is assigned to the ligament model. The material properties set for cervical components are listed in Table 2.

The developed cervical model was experimentally verified against C1-C7 rotations (under moment of 1Nm with respect to the different plane) predicted with those obtained experimentally by Panjabi et al. [10, 11] and numerically by Zhang et al. [12] and Palomar et al. [13]. The simulation for verification and numerical results of Zhang et al. and Palomar et al. were conducted both using the loading and the boundary conditions of the cadaver tests [10, 11].

To explore the role of the uncovertebral joint in the intervertebral motion, the part of the uncovertebral joint of the intervertebral discs in the validated model was removed and replaced with annulus fibrosus layer (Fig. 1(d)). Same loading conditions, adopted in Panjabi et al.'s experiment [11] (i.e., flexion, extension, axial, and lateral bending moments set 0.33 Nm, 0.67 Nm, and 1 Nm), were applied and mechanical responses of the models were analyzed.

3. Results

The ranges of motions for 1Nm on different loading planes were compared with previous experiment and numerical results. Palomar et al.'s study did not include the result of the lateral bending motion. It can be seen that the model predicted the largest motion at the C1/C2 level for the axial rotation loading, while rotational motions for all other cervical segments were significantly less as shown in Fig. 3. Good agreement was found with inter-segmental ROM predicted by our model, which falls within the experimental standard deviation interval, except axial rotational loading. Rotational motions at C2 - C7 levels are greater than experimental results.

Fig. 4 shows that with the uncovertebral joint-replaced model (UJRM), the mobility is reduced in all loading modes. The mobility reduction was found least with flexion. It decreases with the order of extension, axial rotation, and lateral bending motion. It appears that C3/C5 among all the motion segments are most affected; in the sagittal plane motion C3/C4 motion segment is most engaged and in lateral bending and axial rotation C4/C5 is most engaged. The mobility of UJRM is expected to decrease in translation. The magnitudes of translations coupled with angular motions in all directions are illustrated in Fig. 5. Whereas angular motion varies with motion segment, the maximum translation is observed with the upper segments and the translation tends to decrease with lower segments in the sagittal plane motion. The most noticeable translational change in lateral bending motion is detected with the C4/C5 motion segment. Compared to motions described above, axial rotational motion produces relatively irregular translational differences with small magnitudes.

Table 2. Material properties for the cervical spine model.

Component	Young's modulus (MPa)	Poisson's ratio	Cross sectional area (mm^2)	References
Cancellous bone	450.0	0.29	-	[14, 15]
Cortical bone	12000	0.29	t = 1 mm	
End plate	500.0	0.29	-	
AIL	5.0	0.3	20	[12]
TL	10.0	0.3	t = 1 mm	
AcL	5.0	0.3	7.2	
ApL	6.0	0.3	5	[15]
AA-OM	8.0	0.3	33	
PA-OM	6.5	0.3	44	
TM	10.0	0.3	10	
ALL(C0-C1)	8.0	0.3	6	[16]
ALL(C1-C2)	10.0	0.3	6	
ALL(C2-C7)	28.2	0.3	11	
PLL(C2-C7)	25.0	0.3	14	
CL(C0-C2)	2.0	0.3	48	
CL(C2-C7)	4.0	0.3	50	
LF	3.2	0.3	50	[4]
IsL	5.0	0.3	15	
Synovial membrane	12.0	0.4	t = 1 mm	[8]
	Bulk (Mpa)			
Synovial fluid	1666.7	-	-	

AIL=Alar Ligament, TL=Transverse Ligament, AcL=Accessory Ligament,
ApL=Apical Ligament, TM=Tectorial Membrane, LF=Ligamenta Flava,
A(P)A-OM=Anterior(Posterior) Atlanto-Occipital Membrane,
CL=Capsular Ligament, ISL=Interspinous Ligament,
A(P)LL=Anterior(Posterior) Longitudinal Ligament

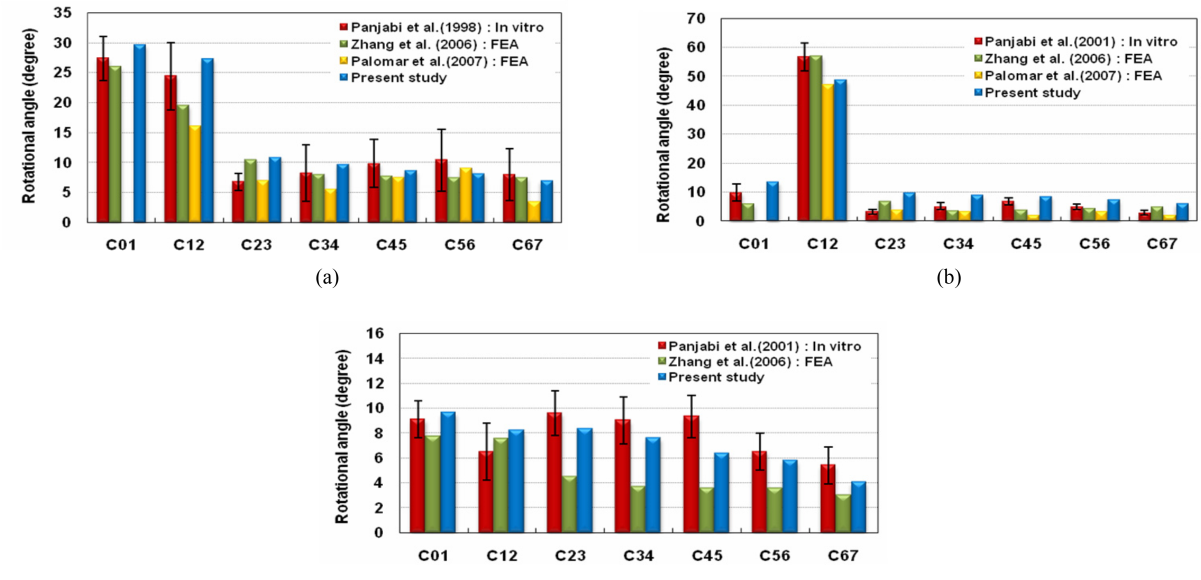


Fig. 3. Comparisons of predicted ROM of each motion segment under: (a) flexion-extension; (b) axial rotation; (c) lateral bending motion. The values for axial rotation and lateral bending summate both right and left sides.

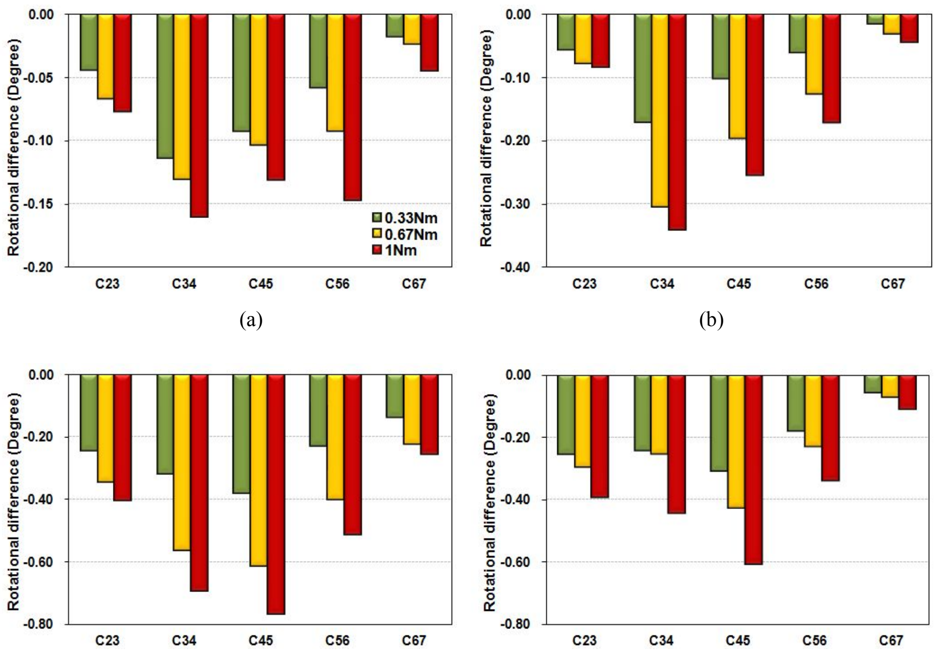


Fig. 4. Predicted rotational difference with a replacement of uncovertebral joints in (a) flexion; (b) extension; (c) lateral bending; (d) axial rotation motion, under various bending moment loads.

The percentage changes in angular and translational motions of UJRM with respect to the original model for the magnitude of imposed moment are shown in Fig. 6. In the comparison against the original model, the most mobility change is found with C4/C5 motion segment under the lateral bending motion. With 1Nm of flexion and extension moment the change rates of the corresponding rotational motions are merely -3.9% and -6.1%, respectively. For axial rotation moment and lateral bending moment -14% and -24.4% are achieved, respectively. Percentage increment in translation appears largest under the axial rotational motion; however, the original model produced 0.00764 mm of translation at C4/C5 as shown in Fig. 5.

Due to the structural configurations of the cervical spine, coupled motions are accompanied with the main motion. Fig. 7 shows the largest coupled motion is produced in the lateral

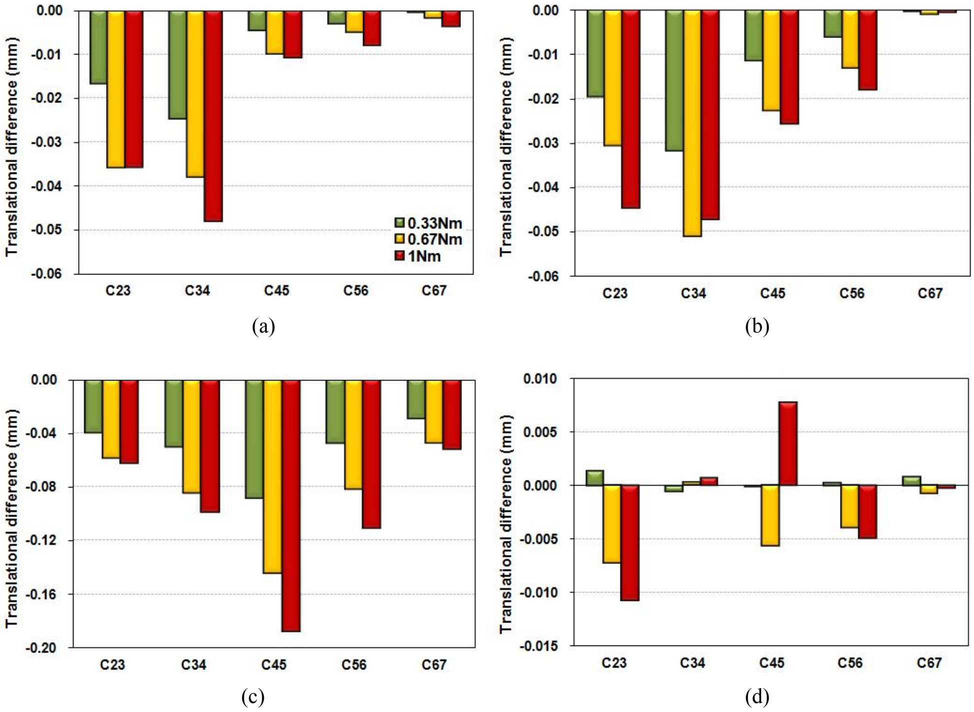


Fig. 5. Predicted translational difference with a replacement of uncovertebral joints in (a) flexion (+X direction); (b) extension (-X direction); (c) lateral bending (+Y direction); (d) axial rotation (+Z direction) motion.

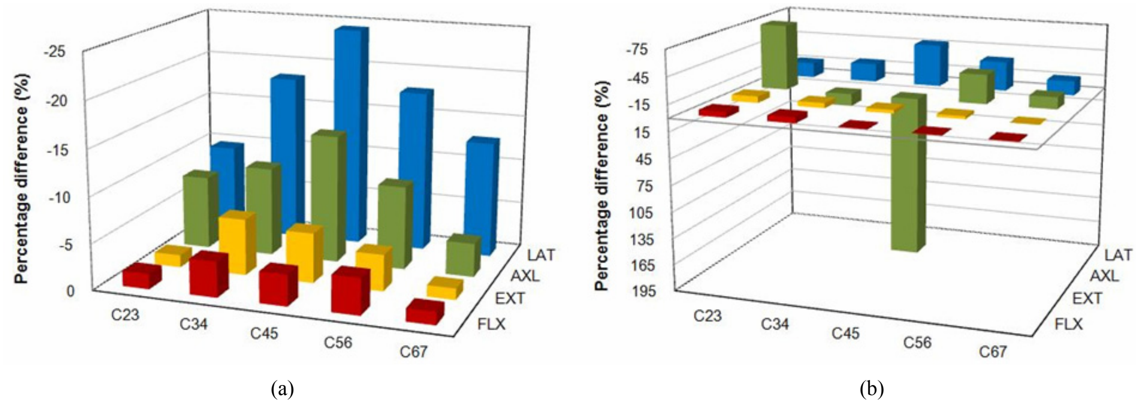


Fig. 6. Predicted percentage difference with a replacement of uncovertebral joints in (a) rotational; (b) translational motion.

bending motion followed by the axial rotation motion. Replacement of the uncovertebral joint with the annulus structure generally reduces the coupled motion in the lateral bending motion, but increased R_x motions are generated in C4/7 motion segments under the axial rotational loading as shown in Fig. 8.

4. Discussion

The presence of the uncovertebral joint and uncinate process makes the cervical vertebrae distinct from the rest of the vertebrae. In addition to the two unique features involving the uncovertebral joint and uncinate process, it should be noted that the angle between the facet joints is relatively small compared to those with the thoracic vertebrae and the lumbar vertebrae. The joints overlap one another in the coronal plane and are oriented approximately 45° from the horizontal in the sagittal plane. Due to its unique orientation and relatively flat articulating surface, the facet joint in the cervical spine allows relatively large range of motion.

Due to the above-mentioned features, rotation and translation involving the cervical vertebrae are expected to be relatively larger than other spinal columns. The uncinate process serves to effectively control the translation while it limits the rotation of the intervertebral disc. In our model, the size of uncinate process was relatively small, which induced more flexibility in C2 to C7 motion segments under axial rotational loading compared with Panjabi et al.'s experimental results

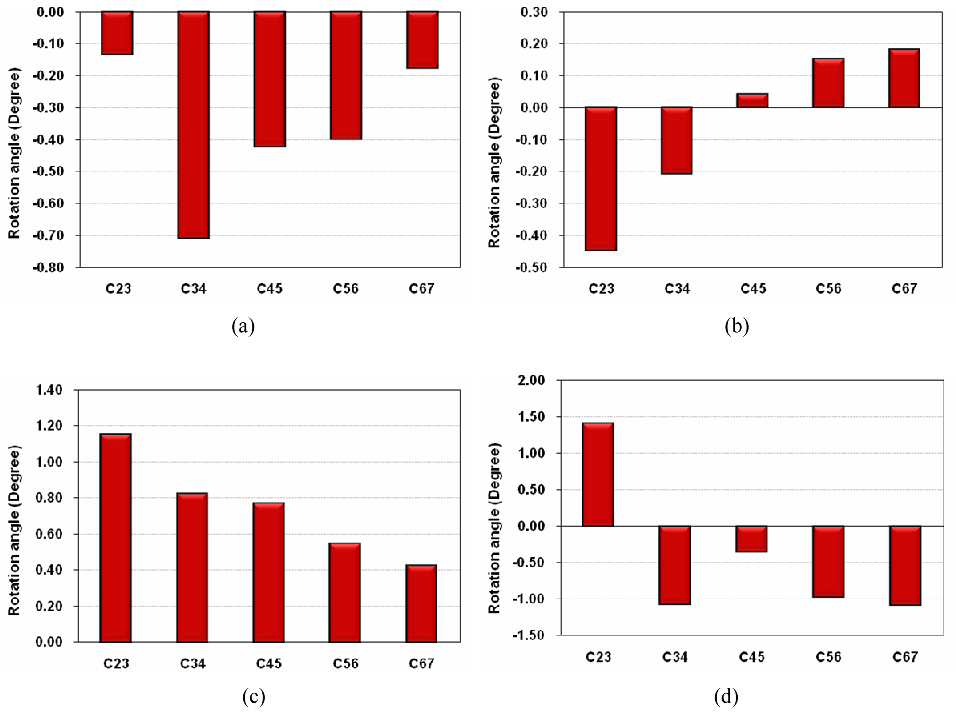


Fig. 7. Magnitudes of coupled rotational motions in the original model: (a) R_Y; (b) R_X motions are accompanied in the axial rotation motion; (c) R_Y; (d) R_Z motions are accompanied in the lateral bending motion.

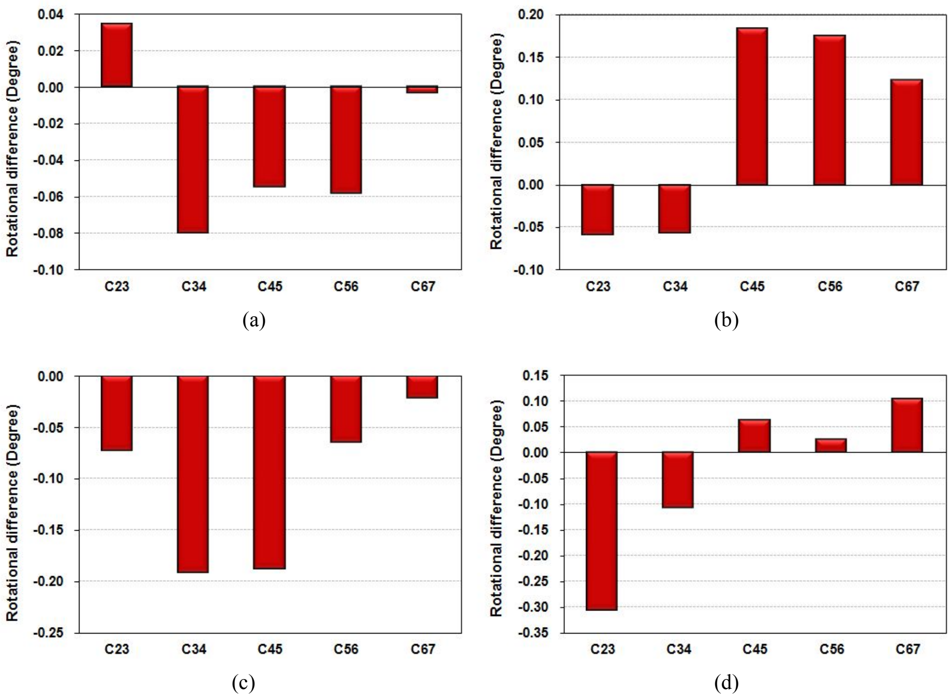


Fig. 8. Difference of the coupled rotational motion between original and UJRM: (a) R_Y; (b) R_X motions are accompanied in the axial rotation motion; (c) R_Y; (d) R_Z motions are accompanied in the lateral bending motion.

[10, 11] as shown in Fig. 3. The uncovertebral joint is expected to help to partially restore the rotational motion, which is, however, limited by the uncinate process. The present results confirm that as demonstrated in Fig. 4 the uncovertebral joint is largely engaged in lateral bending and axial rotation especially the upper part between C2 through C5 being engaged the most among others. The maximum percentage change (24%) is found with C4/C5 when 1 Nm of lateral

bending moment is loaded, whereas the change with C5/C7 in the amount of rotation and translation is considerably small. The uncinate process is relatively small in size, compared to the lateral side of the disc, leading to the conclusion that the contribution to the motion of the uncovertebral joint with the lower part is less significant. Clausen et al. [4] uniquely studied the contribution of the uncovertebral joint to the body motion. Based on their study using the single segment of C5/C6, it was found that with the annulus replacing the uncovertebral joint, the percentage changes in motion under 1.8 Nm loading condition were -13, -15, -17 and -36% for flexion, extension, axial rotation and lateral bending, respectively. However, the present authors predicted that the values corresponding to the previous results by Clausen et al. are -3.9, -6.1, -14, and -24% under 1Nm. The difference lies in the fact that they modeled the uncovertebral joint with the gap element, whereas the present authors adopted the fluid element. The second reason introducing the difference is that they modeled the uncinate process in conjunction with the lower level (C5/C6), which is small. The third reason is that Clausen et al.'s study only engaged the single motion segment. Therefore, it can be argued that with their set-up, the relatively extensive motion involving C0/C2 cannot be properly accounted. The level providing the maximum difference between the results is C5/C6, C3/C4 and C4/C5 for flexion, extension and the axial rotation/lateral bending, respectively. Despite the level difference between the results from the two models, it is agreed that the change of the motion appears largest with the motion associated with the lateral bending and the next largest change can be found with axial rotation. The changes with flexion and extension appear to be relatively less.

Based on the histological study by Brismée et al. [2], the uncovertebral complex is to associate a synovial joint but it is still yet to be evaluated in order to claim that the joint performs as a synovial joint. Since contact behavior was not addressed in the present results, the model needs to be further improved to reflect the realistic behavior of the uncovertebral joint in future.

At each segment of the cervical vertebrae subject to lateral bending moment and moment in the axial rotation, coupled motions are induced as shown in Figs. 7 and 8.

In association with the configuration of each vertebra and its various passive elements, coupled motions are found induced. With axial rotation moment applied, the coupled lateral bending motion (Rx) is induced and the directions of the motion at the upper levels and lower levels are opposite. The uncovertebral joint appears to allow extending the range of the coupled motion. The differences produced by the role of muscles (not accounted in the present study) could be observed; the neighboring muscles will tend to limit the coupled motion which is introduced in the cervical column. Translation associated with rotation is amplified due to presence of the uncovertebral joint, and especially the change appears relatively large with the lateral bending. Thereby, the cervical spinal column involves larger motion compared to thoracic spine or lumbar spine.

Recently, the number of the total disc replacement (TDR) surgeries has increased. Based on the present results, it can be predicted that the stability of the motion segment largely depends on the size of the parts removed from the uncovertebral joint and uncinate process in the TDR surgery. Snyder et al. [17] suggested, based on their in-vitro experiment, that in the TDR surgery the amount of motion of the corresponding segment varies with the size of part removed in uncinatectomy. Therefore, it is likely that the device performing as the same shape of artificial disc used in the TDR surgery for lumbar spine is rather inadequate with the TDR surgery for the cervical vertebrae. It is believed that the biomechanical analysis studying the case where the artificial disc is used to conduct a surgical removal in the uncovertebral joint and uncinate process provides significant clinical data. Furthermore, the biomechanical analysis can be used to help develop an artificial disk optimally designed for segments of the cervical spine.

5. Conclusion

In the present finite element model, the function of uncovertebral joint was analyzed. It was observed that the role of uncovertebral joint varies with the size of the uncinate process at each level of the cervical vertebrae; especially, motions increase greatly with the lateral bending followed by axial rotation. In the present study, the contact behavior is not addressed since the uncovertebral joint is modeled with a fluid element; thus the cervical spine model is needed to integrate further details including the contact phenomena in the uncovertebral joint. The neighboring muscles, which also control the motion of the cervical spine, still remain to be integrated. It is believed that based on a series of studies on the cervical spine, a basis of significant data can be achieved to help promote improvement in TDR device design.

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References

[1] P. Ghosh, *The biology of the intervertebral disc*, CRC Press, Boca Raton, Florida, USA (1988) 80.
[2] J. M. Brismée, P. S. Sizer Jr., G. S. Dedrick, B. G. Sawyer and M. P. Smith, Immunohistochemical and histological study of human uncovertebral joints: a preliminary investigation, *Spine*, 34 (12) (2009) 1259-1263.
[3] S. Kumaresan, N. Yoganandan and F. A. Pintar, Methodology to quantify human cervical spine uncovertebral joint anatomy, *J. Musculoskeletal Res*., 1 (2) (1997) 131-139.
[4] J. D. Clausen, V. K. Goel, V. C. Traynelis and J. Scifert,

Uncinate processes and luschka joints influence the biomechanics of the cervical spine: quantification using a finite element model of the C5-C6 segment, *J. Orthop. Res*., 15 (3) (1997) 342-347.
[5] Digimation, Inc., *Human Anatomy NURBS model*, Lake Mary, Florida, USA (2009).
[6] N. Milne, The role of zygapophysial joint orientation and uncinate processes in controlling motion in the cervical spine, *J. Anat*., 178 (1991) 189-201.
[7] I. Gilad and M. Nissan, Sagittal evaluation of elemental geometrical dimensions of human vertebrae, *J. Anat.,* 145 (1985) 115-120.
[8] N. Yoganandan, S. Kumaresan and F. A. Pintar, Biomechanics of the cervical spine Part 2, Cervical spine soft tissue responses and biomechanical modeling, *Clinical Biomechanics*, 16 (2001) 1-27.
[9] J. S. Pooni, P. F. Harris, R. C. Hilton and K. E. Davies, Comparison of the structure of human intervertebral discs in the cervical, thoracic and lumbar regions of the spine, *Surg. Radiol. Anat*., 8 (3) (1986) 175-182.
[10] M. M. Panjabi, K. Nibu and J. Cholewicki, Whiplash injuries and the potential for mechanical instability*, Eur Spine J*., 7 (6) (1998) 484-492.
[11] M. M. Panjabi, J. J. Crisco, A. Vasavada, T. Oda, J. Cholewicki, K. Nibu and E. Shin, Mechanical properties of the human cervical spine as shown by three-dimensional load-displacement curves, *Spine*, 26 (24) (2001) 2692-2700.
[12] Q. H. Zhang, E. C. Teo, H. Wan and V. S.lee, Finite element analysis of moment-rotation relationships for human cervical spine, *J. Biomechanics*, 39 (2006) 189-193.
[13] A. P. Palomar, B. Calvo and M. Doblare, An accurate finite element model of the cervical spine under quasi-static loading, *J. Biomechanics*, 41 (2008) 523-531.
[14] E. C. Teo and H. W. Ng, First cervical vertebra(atlas) Fracture mechanism studies using finite element method, *J. Biomechanics*, 34 (2001) 13-21.
[15] K. Brolin and P. Halldin, Development of a finite element model of the upper cervical spine and a parameter study of ligament characteristics, *Spine*, 15 (4) (2001) 376-385.
[16] N. Maurel, F. Lavaste and W. Skalli, A three-dimensional parameterized finite element model of the lower cervical spine. Study of the influence of the posterior articular facets, *J. Biomechanics*, 30 (1997) 921-931.
[17] J. T. Snyder, M. N. Tzermiadianos, A. J. Ghanayem, L. I. Voronov, A. Rinella, A. Dooris, G. Carandang, S. M. Renner, R. M. Havey and A. G. Patwardhan, Effect of uncovertebral joint excision on the motion response of the cervical spine after total disc replacement, *Spine*, 32 (26) (2007) 2965-2969.

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